NACA

RESEARCH MEMORANDUM

SPARK IGNITION OF FLOWING GASES

II - EFFECT OF ELECTRODE PARAMETERS ON ENERGY REQUIRED TO IGNITE A PROPANE-AIR MIXTURE

By Clyde C. Swett, Jr.

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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SUMMARY

Research was conducted to determine the effect of the electrode parameters of spacing, configuration, and material on the energy required for ignition of a flowing propane-air mixture. In addition, the data were used to indicate the energy distribution along the spark length and to confirm previous observations concerning the effect of spark duration on ignition energy requirements. The data were obtained with a mixture at a fuel-air ratio of 0.0835 (by weight), a pressure of 3 inches of mercury absolute, a temperature of 80° F, and a mixture velocity of 5 feet per second.

Results showed that the energy required for ignition decreased as the electrode spacing was increased; a minimum energy occurred at a spacing of 0.65 inch for large electrodes. For small electrodes, the spacing for minimum energy was not sharply defined. Small-diameter electrodes required less energy than large-diameter electrodes if the spacing was less than the optimum distance of 0.65 inch; at a spacing equal to the optimum distance, no difference was noted. Significant effects of electrode material on ignition energy were ascribed to differences in the type of spark discharges produced; glow discharges required higher energy than the arc-glow discharges. With pure glow discharges, the ignition energy was substantially constant for lead, cadmium, brass, aluminum, and tungsten electrodes. A method is described for determining the energy distribution along a glow discharge. It was found that one-third to one-half of the energy in the spark was concentrated in a small region near the cathode electrode, and the remainder was uniformly distributed across the spark gap. It was impossible to ascertain the dependence of ignition on this distribution. It was also observed that long-duration (600 microsec) sparks required much less energy for ignition than did short-duration (1 microsec) sparks.

INTRODUCTION

In order to provide information for the design and operation of jet-engine combustors, research is being conducted at the NACA Lewis laboratory to study the fundamental variables affecting ignition and combustion of fuel-air mixtures. As a part of this research, the parameters which may influence the energy required for a spark to ignite homogeneous fuel-air mixtures are being investigated.

Previous studies (reference 1) have shown the effect on ignition energy of three gas parameters - mixture pressure, velocity, and fuel-air ratio - and one spark parameter - spark duration. Three additional spark variables which may affect the required energy include electrode spacing, configuration, and material. These variables have been studied to a limited extent with short-duration sparks (approximately 1 microsec) produced by discharging a capacitor directly into the spark gap. It is shown in references 2 and 3 that under these conditions electrode material has no effect on the required energy and that electrode configuration and electrode spacing have a large effect. The effect of these parameters with sparks of long duration (greater than 100 microsec) has not been studied to any appreciable extent. The data available (for example, references 4 and 5) indicate some energy changes with the electrode variables; the energy changes are calculated from observed transformer primary current variations. Because electrode parameters may alter the manner in which the energy is distributed along the spark and the type of discharge produced in the secondary circuit, a calculated energy change may or may not be real. Thus the relation among electrode variables, ignition energy, and types of discharge requires further investigation in order to determine precise ignition energy effects.

From the fundamental processes of electrical discharges in gases it can be shown that the voltage along the spark does not vary in a linear manner between the electrodes. It can be concluded, then, that the spark energy is distributed nonuniformly. At the present time no information is available concerning the effect of this nonuniform distribution on the ignition process. Since previous investigators (references 4 and 5) have shown some differences in ignition energy for different electrode materials, the determination of the energy distribution as a function of electrode material may serve to indicate the spark region or regions which affect the ignition process.

The present investigation was conducted to (1) provide more precise ignition energy data on the effect of electrode variables with long-duration sparks and (2) attempt to determine the distribution of energy along the spark discharge and to ascertain the dependence of ignition on this distribution. The investigation has, as secondary objectives, the study of spark discharge characteristics and the comparison of energy requirements with long- and short-duration discharges.

Ignition energy data are presented herein for one mixture condition only: mixture pressure, 3 inches mercury absolute; temperature, 80° F; velocity of mixture past the electrodes, 5 feet per second; and fuel-air ratio (by weight), 0.0835. A spark duration of 600 microseconds was chosen on the basis of experimental feasibility and was used throughout the investigation. At these mixture and spark-duration conditions, ignition energy measurements were made with six different electrode 2394 materials and a wide range of electrode spacings (0.23 to 0.80 in.).

APPARATUS AND PROCEDURE

The combustion apparatus and ignition and energy-measuring system previously described (references 1 and 6) were used for the present investigation. The combustion apparatus consisted of a means for thoroughly mixing propane and air and for passing the combustible mixture through a 3-inch-diameter duct in which the spark electrodes were located diametrically opposed to each other. The ignition system (fig. 1) consisted of a means for charging a storage condenser and discharging it through two paths: (1) resistor R_1, and (2) a path consisting of R_2, the spark gap, and R_3 in series. Negligible current passes through resistors R_4 and R_5. The energy of the spark was determined by obtaining a trace of the voltage-current-time characteristic of the discharge on the screen of a cathode-ray oscillograph. The voltage of the discharge was reduced by the voltage divider (R_4 and R_5) and placed on the vertical plates of the oscillograph. The current of the discharge was obtained by placing the voltage produced across R_3 onto the horizontal plates. An oscillator connected to the z-axis amplifier of the oscillograph provided the necessary timing marks. The resulting trace was photographed and analyzed for energy quantities.

The ignition and energy-measuring system employed herein contained some modifications and refinements which were not present in the system described in reference 1. The capacitance of the storage condenser with the present tests was 0.625 microfarad, and values of resistors were such that a spark duration of approximately 600 microseconds was produced. A variable high-voltage condenser having 10 to 20 micromicrofarads capacitance was placed across R_4 in order to balance the capacitance of the vertical deflection-plate leads and the vertical deflection plates. This condenser was used so that the true value of any sudden surges or high-frequency components could be observed. The effect of this consenser on the energy measurements was negligible at the operating conditions chosen. In order to extend the applicability of the system to other conditions, the voltage divider was balanced by the following method: A 60-cycle voltage wave was applied to the voltage divider and the reduction factor was determined. A 1-megacycle wave was then applied and the condenser adjusted to give the same reduction factor. The reduction factor was then independent of frequency within this range. The divider must be rebalanced when R_4 or R_5 are changed. At large values of R_5, a negative pulse appears at the vertical plates because the capacitance between the upper oscilloscope plate and ground is different from that between the lower plate and the ground. For this reason the ground point was shifted from the bottom side of R_3 to the position shown. As a result of this change, however, a capacitance of 500 to 1000 micromicrofarads exists across R_3 with considerable stray capacitance from the high-voltage end of the condenser to ground. When switch S_2 is closed, the high-voltage end tends to remain momentarily at the high potential since the stray capacitance is charged, resulting in a negative pulse appearing across R_3. For the present tests, with the values of R_3, R_4, and R_5 used, no difficulty was experienced with the ground in either position. At higher pressures, where values of R_2, R_3, R_4, and R_5 must be larger, it is recommended that the circuit with the ground on the bottom of R_3 be used in conjunction with a voltage divider that balances each of the vertical deflection plates to ground. Preliminary tests with such a divider (fig. 2) appear satisfactory.

RESULTS AND DISCUSSION

Effect of Electrode Variables

Effect of electrode configuration and spacing. - The effect of electrode configuration and spacing on the energy required for ignition of a 0.0835-fuel-air ratio propane-air mixture at a pressure of 3 inches of mercury absolute is presented in figure 3. Data for stainless steel 3/16-inch rods, 0.025-inch rods, and needle electrodes showed that the energy required for ignition decreased as the electrode spacing was increased. Minimum energy was required at a spacing of 0.65 inch for the large electrodes. With the small electrodes the spacing for minimum energy was not sharply defined. At spacings of less than 0.65 inch, the larger rod electrodes required much higher energies than did the smaller rod and needle electrodes because of flame quenching on the increased surface area of the larger electrodes. The increase in ignition energy required by the needle electrodes over that required by the 0.025-inch rods may possibly be due to differences in the manner in which the energy is distributed for sharp points and rods. At a spacing of 0.65 inch, all the electrodes required the same energy. This distance is approximately the quenching distance (distance marking the farthest penetration of the flame-quenching effect of the solid electrode material) for this particular pressure condition. A quenching distance of 0.638 inch has been determined in reference 7.

Previous data (reference 1) for a 0.025-inch spacing with 3/16-inch Inconel electrodes are also indicated in figure 3. The required energy of 33 millijoules is substantially less than the 56-millijoule value obtained in the present investigation. The value of 56 millijoules, however, had occasionally been required in the previous investigation; similarly, in the present tests, 56 millijoules represents the most consistent value although on occasion the value of 33 millijoules was obtained. The apparent lack of reproducibility has been explained on the basis of the type of discharge (arc or glow) produced.

2394

Types of discharge. - The spark characteristics obtained with 3/16-inch rod electrodes spaced at 0.25 inch are compared in figures 4(a) and 4(b) for the previous (reference 1) and present investigations. The oscillograms indicate the variation of voltage and current of the spark with time. The previous data obtained show that as the current decreased during the life of the discharge, the voltage gradually decreased until, at a point indicated as the transition point, the voltage increased abruptly, accompanied by a tendency for instability. This discharge originated as an arc discharge and, at the transition point, changed to a glow discharge. (The chief differences between the arc and glow discharges lie in the much higher current density and lower voltage drop at the cathode electrode for the arc discharge.) The instability resulted in rapid oscillations back and forth between glow and arc discharges. The present data show a smooth curve characterized by considerably higher voltages in the initial stages of the discharge. This discharge was a glow discharge. A slight instability occurred at two points on the curve, as indicated by the pips on the lower side of the trace.

The physical appearances of the arc and glow discharges were different, as can be seen in figures 4(c) and 4(d). The pictures were obtained with 3/8-inch-diameter spherical electrodes. With the arc-glow discharge, a discharge that originated as an arc and ended as a glow, a bright spot appeared on the anode and the cathode. Generally, if the discharge was predominantly an arc, the cathode spot was bright; if the glow discharge existed for a considerable time, the spot was diffused as in the photograph. The glow discharge was characterized by a glow over a considerable portion of the cathode surface and by a dark area (Faraday dark space) immediately before the cathode. The same differences were observed with needle electrodes; however, since considerable surface area is required for the discharge from the cathode to take place, the glow appeared on the surface of the needle electrodes as far as 1/2 inch from the point.

Wide variations in ignition energies are possible at conditions where two types of discharge may occur; a glow discharge requires higher ignition energies than the arc discharge.

Effect of electrode material and spacing: small-diameter electrodes. - The effect of electrode material and spacing is shown in figure 5 with a comparison of energy requirements for small-diameter (0.025-in.) rods of stainless steel and cadmium. The curves show that for these electrodes the energy does not vary significantly with spacing and that the energy requirement with the stainless steel electrodes is about 50 percent higher than with the cadmium electrodes. An examination of the oscillograms showed that the discharge was of the arc-glow type for the cadmium and of the glow type for the stainless steel. The apparent differences in energy may thus be attributed to the different types of discharge obtained. After many trials, a glow discharge was obtained with cadmium electrodes at a spacing of 0.65 inch and the energy value was comparable to that obtained with the stainless steel electrodes.

Effect of electrode material: spherical electrodes. - Since comparison of materials under identical types of discharge is desirable, an attempt was made to produce consistent glow discharges for a number of electrodes by making the electrodes of large size. Spheres 3/8 inch in diameter were used to obtain the following ignition data at a spacing of 0.65 inch:

Metal	Ignition energy (millijoules)	Type of discharge
Cesium oxide (coating)	13.4 ±0.5	Arc-glow
Lead	17.1 ±0.5	Glow
Brass	17.8 ±0.5	Glow
Cadmium	18.6 ±0.5	Glow
Aluminum	19.4 ±0.7	Glow
Tungsten	19.6 ±0.9	Glow

Of the six electrodes tested, only the electrodes with cesium oxide coatings did not give a glow discharge. With the other electrodes, reproducibility of data was about ±3 percent for the lead, cadmium, and brass electrodes; ±4 percent for aluminum; and ±5 percent for tungsten. A variation of ±3 percent can be attributed to the fact that the spark does not always occur in a straight line between electrodes but has a curvature which may lengthen the spark as much as 10 percent. The larger variation with aluminum and tungsten may be due to an abnormal glow discharge (see appendix). Thus for electrodes producing the same type of discharge, the variation of ignition energy with electrode material was within experimental accuracy and must be considered negligible.

Distribution of Energy along Spark Discharge

In the appendix it is shown that the total energy in the glow discharge may be divided into two major parts: one part in a region extremely close to the cathode electrode, and the other uniformly distributed along the rest of the discharge path, or the positive column.

Because of the negligible effect of electrode material on the ignition energy, determinations of cathode and positive-column energies cannot be used to distinguish the part of the discharge which controls the ignition process. It is of interest, however, to note the approximate amounts of energy that are released in the various regions. The distribution of energy in the glow discharge with each of the five electrodes was determined by the method described in the appendix. The results are shown in the following table:

2394

Metal	Ignition energy (millijoules)	Cathode energy (millijoules)	Positive-column energy (millijoules)
Lead	17.1 ±0.5	8.4 ±0.08	8.7 ±0.42
Brass	17.8 ±0.5	7.8 ±0.08	10.0 ±0.42
Cadmium	18.6 ±0.5	7.3 ±0.07	11.3 ±0.43
Aluminum	19.4 ±0.7	5.8 ±0.1	13.6 ±0.6
Tungsten	19.6 ±0.9	8.5 ±0.3	11.1 ±0.6

The data indicate that approximately one-third to one-half of the energy is concentrated in the cathode region, while the remainder is uniformly distributed across the spark gap.

Comparison of Long- and Short-Duration Sparks

A comparison of ignition energy requirements for long- and short-duration sparks is shown in the following table:

Spark duration (microsec)	Mixture velocity (ft/sec)	Fuel-air ratio	Electrode spacing (in.)	Ignition energy (millijoules)
~1	[a]0	[a]0.0802	[a]0.638	[a]22.7
~1	0	.0835	.650	22 - 24
~1	5	.0835	.650	34 - 36
600	5	.0835	.650	[b]10.7 - 19.6

[a]Data from reference 7.
[b]Value depends upon type of discharge and electrode.

Because air dielectric condensers such as used in reference 7 were unavailable, solid dielectric condensers were used for the short-duration spark tests although poor reproducibility may be expected with such condensers. The results obtained at zero velocity, however, agree favorably with those of reference 7; hence, the method and equipment used are comparable. A comparison of the energy values for the mixture flowing at a velocity of 5 feet per second indicates that the 1-microsecond spark requires 1.5 to 3 times more energy than the 600-microsecond spark.

In an attempt to explain the increased energy requirements with the short-duration spark discharges, photographs were obtained at energies slightly below the values required for ignition; 3/8-inch-diameter spheres were used for the short-duration spark and 0.025-inch rods for the long-duration spark. (The type of electrode has no effect on the general appearance of the various discharge zones.) These photographs show distinct differences in the appearances of the zone around the short- and long-duration sparks (fig. 6). With the short-duration spark, the bright core of the spark always appeared to be surrounded by a luminous cylinder from which two luminous zones occasionally propagated and then extinguished. These zones are not visible when air is used in place of the combustible mixture. The long-duration spark produced a similar luminous cylinder around the spark; however, the luminous zone which occasionally propagated from this cylinder appeared to exist only on one side (in general, downstream) of the spark. The core of the long-duration spark appeared quite uniform, whereas the core of the short-duration spark appeared to be brighter toward the electrodes and weaker and more diffused at the center. It appears reasonable, then, to assume that the differences in igniting ability of the long- and short-duration sparks are due to differences in the distribution of energy; the short-duration spark produces more concentrated zones of energy release. At the present time no method is available for determining the distribution of energy in the short-duration spark.

2394

SUMMARY OF RESULTS

The following results were obtained in an investigation of the effect of electrode variables on the energy required in a spark of 600 microseconds duration to ignite a flowing propane-air mixture:

1. The energy required for ignition decreased and then increased as the electrode spacing was increased; a minimum energy was required at a spacing of 0.65 inch for large-diameter electrodes. With small-diameter electrodes the spacing for minimum energy was not sharply defined.

2. Small-diameter electrodes required less energy than large-diameter electrodes if the spacing was less than optimum; no effects of electrode size were observed at the optimum spacing of 0.65 inch.

3. For similar glow discharges the ignition energy was negligibly affected by variation in electrode materials including lead, cadmium, brass, aluminum, and tungsten electrodes. Arc discharges, produced by certain electrodes, required less energy to produce ignition than did glow discharges.

4. A method for determining the energy distribution along the spark was developed which indicated that one-third to one-half of the energy

of the discharge was concentrated in a small region near the cathode electrode, a negligible amount was present in the anode region, and the remainder was uniformly, distributed across the spark gap. It was impossible to ascertain the dependence of ignition on this distribution.

5. Long-duration (600 microsec) sparks required much less energy for ignition than did short-duration (1 microsec) sparks.

2394

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APPENDIX - METHOD USED TO DETERMINE ENERGY DISTRIBUTION ALONG SPARK DISCHARGE

A brief review of some of the applicable characteristics of electric discharges in gases is necessary in order to understand the method used to determine the energy distribution along a spark discharge path. Comprehensive treatment of these characteristics may be found in references 8 and 9.

2394

Voltage Distribution along Constant-Current Discharge

Consider a discharge of constant current to exist between two electrodes as in figure 7. If, by some means, the voltage is determined along the path of the discharge, the voltage will vary substantially as indicated in the figure. At the negative or cathode end of the discharge there is a large voltage change which is defined as the cathode drop. This cathode drop can represent a considerable portion of the total voltage drop of the glow discharge and occurs within a distance of a few electron-mean-free paths from the cathode. The drop is affected by current, pressure, work function of the electrode, type of gas, impurities in the metal and gas, electrode surface condition, and electrode configuration. Beyond the cathode region there is a region (positive column) occupying most of the discharge length in which the voltage increases linearly with distance. At the end of this column there is another voltage change defined as the anode drop. This drop compares, in magnitude, with the ionization potential of the gas or about 10 to 15 volts and occurs extremely close to the anode.

If the anode is moved toward the cathode, other conditions remaining constant, it will be found that the cathode drop remains unchanged. The only effect will be a decrease in the positive column length and, consequently, in its voltage drop. By a sufficient decrease in electrode spacing the positive column can be made to disappear completely, with the anode and cathode drops remaining unchanged. Since in the glow discharge the anode drop is small compared with the cathode drop it may be neglected. Thus the method for measuring cathode voltage drop consists in measuring the total voltage drop at various spacings and plotting voltage against spacing as in figure 7. The straight line drawn through these points will intersect the zero spacing axis at the cathode voltage drop (assuming this drop occurs within a negligible distance from the cathode).

A very important consideration in the determination of energy distribution concerns the effect of current variations on the cathode drop. The dependence of the cathode voltage drop on current is given qualitatively in figure 8 for the regions of interest. As the current is increased from point E the voltage remains constant to point F. The region between E and F is defined as the normal glow discharge region. From points F to H the voltage increases; this region is defined as the abnormal glow discharge region. From H to K the voltage decreases through a transition region with an arc discharge originating at point K. The cathode drop in the arc discharge can decrease to the order of magnitude of the ionization potential (10 to 15 volts). Frequently the curve may be discontinuous between H and K, or the peak at H may not be observed; that is, the discharge may change from an arc to a normal glow without passing through the abnormal glow region. The total voltage curve is, of course, the sum of cathode, anode, and positive column voltages and its shape is similar to the curve shown.

Determination of Cathode Voltage Drop in Spark Discharge

The current in the spark discharge used to obtain ignition data was varying continuously so that a slight modification of the cathode voltage drop method previously described was necessary. After an ignition spark and oscillogram had been obtained at the optimum spacing, the spacing was reduced. Oscillographic data were obtained again using the same initial settings of the ignition source. In this case, no ignition occurred because the electrodes were within the quenching distance. Similar data were obtained for a number of different spacings and electrodes. The voltage-current curves as read from the oscillograms for the various electrodes are shown in figure 9. Constant-current cross plots of the brass electrodes (fig. 9(b)) are shown in figure 10. Straight lines were obtained with the intersection points of the lines at the vertical axis representing the cathode voltage drops.

The cathode voltage curves obtained for five metals are shown in figure 11. The cathode voltage drop with cadmium and brass electrodes was independent of current and thus indicated a normal glow discharge. With lead electrodes, a slight increase in cathode drop occurred at the lower current values. A large increase in cathode drop with an increase in current was observed with tungsten, which is characteristic of an abnormal glow discharge. A part of the aluminum cathode drop curve might also indicate an abnormal glow discharge. The fact that the aluminum and tungsten discharges may originate in an unstable abnormal glow discharge region may explain the increased variation in results obtained with these electrodes. The cathode drop may vary from spark to spark, affecting the total voltage, and hence the measured energy.

Values of the cathode drops determined in this manner were plotted (fig. 12) against work function values of metals obtained from references 8 and 10. The range of values of both cathode drop and work function are indicated in figure 12. The cathode drop increases approximately with work function, in agreement with results of reference 8.

Correlation of Spark Discharge Voltage with Cathode Voltage Drop, Electrode Spacing, and Spark Discharge Current

In order to further characterize cathode voltage drop, an empirical correlation relating the total voltage drop with cathode voltage, electrode spacing, and spark current was developed. Since, for a constant current, the gap voltage increases linearly with spacing, the voltage per unit length of the positive column is constant. This voltage gradient can be determined and plotted as a function of current. From these data an empirical equation relating spark voltage to cathode drop, electrode spacing, and current was determined. The empirical equation for brass spheres is

2394

$$V_S = V_c + 360\ s + 3460\ si$$

where

V_S spark voltage, volts

V_c cathode voltage drop, volts

s electrode spacing, inches

i current, amperes

In figure 13 values of the spark voltage are plotted against the values obtained from the equation. Data for the current values below 0.02 ampere are not shown since at these currents the discharge is easily extinguished and its behavior may be erratic. The correlation is less precise in the initial stage of the discharge where a higher voltage may be necessary to produce the required amount of ionization. Additional errors are expected because of variations in spark length resulting from curvature of the spark. The equation shows that the voltage increases linearly with spacing if the current is constant and increases linearly with current if the spacing is constant. The positive column thus simulates an electric resistance.

Determination of Cathode-Region and Positive-Column Energies

Once the cathode drops are known, the energy dissipated in the cathode region is determined by the method used for the measurement of ignition energy, that is, an integral of the product of voltage, current, and time. The current is obtained from the oscillograms. The energy dissipated in the positive column is obtained by subtracting the cathode energy from the total ignition energy.

2394

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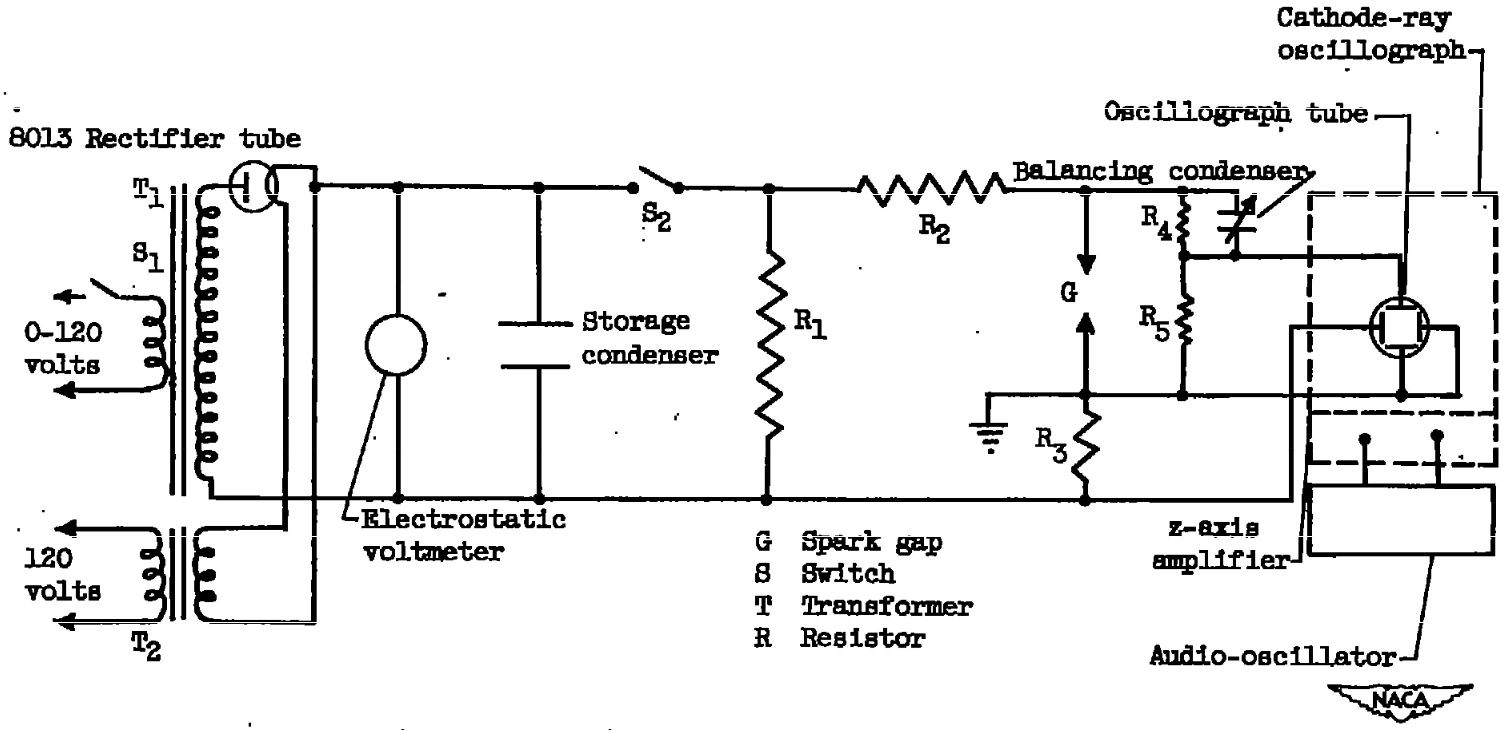

Figure 1. - Modified ignition and energy-measuring systems for long-duration sparks.

2394

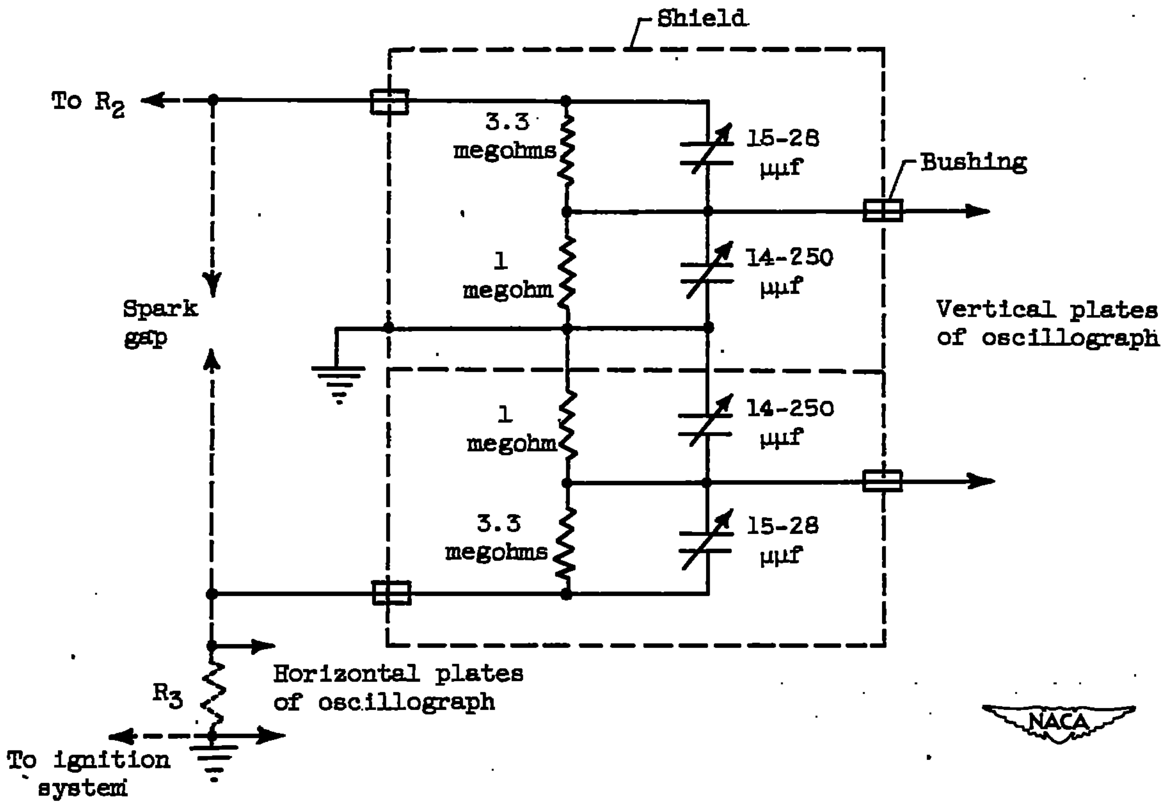

Figure 2. - Balanced capacitance-resistance voltage divider for spark-ignition energy measurements.

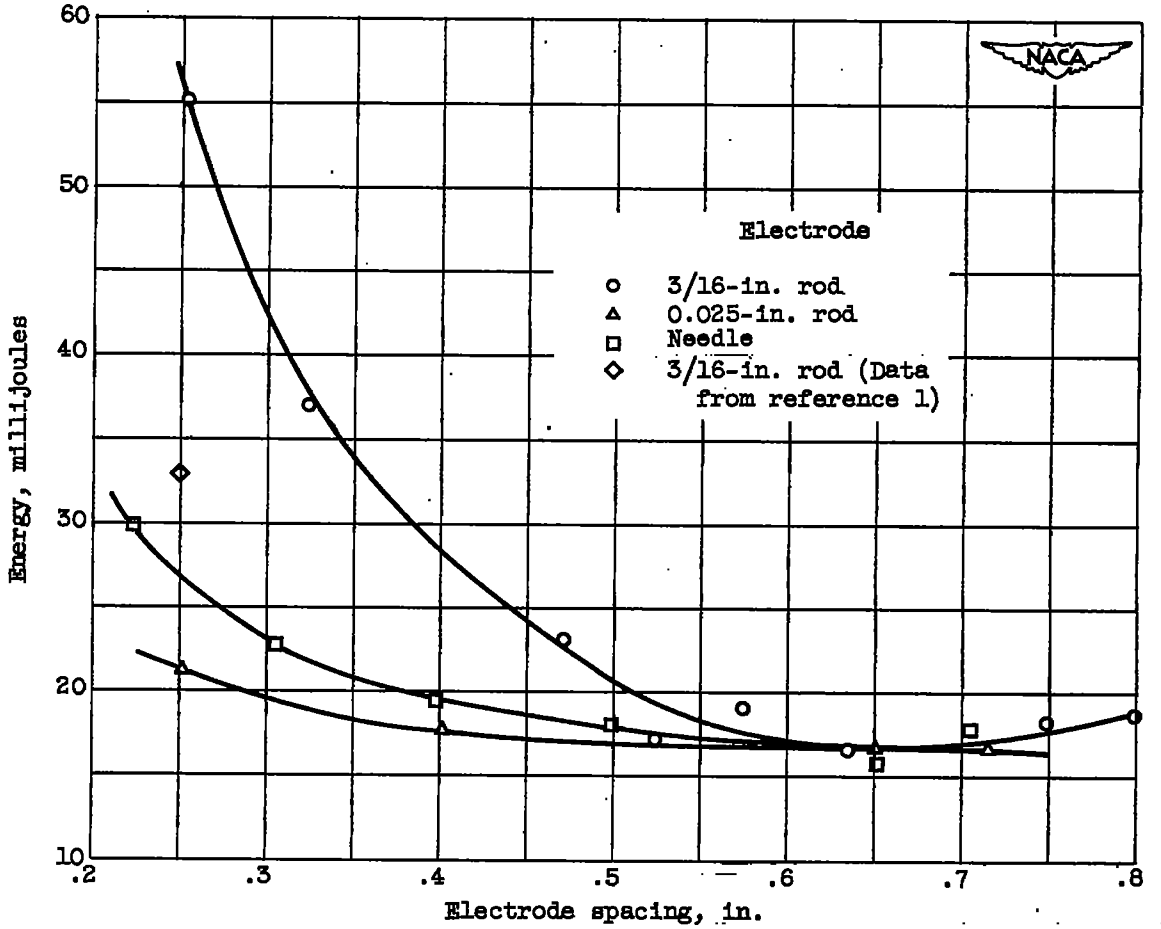

Figure 3. - Effect of electrode configuration and spacing on ignition energy of flowing propane-air mixture. Pressure, 3 inches mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835.

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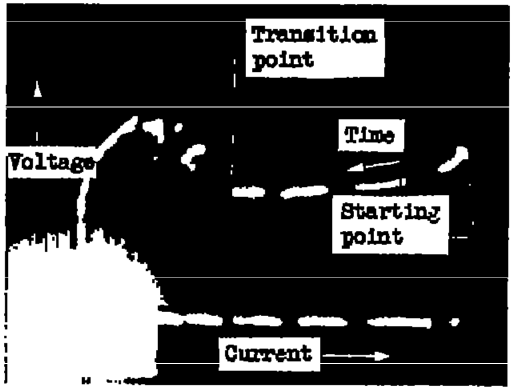
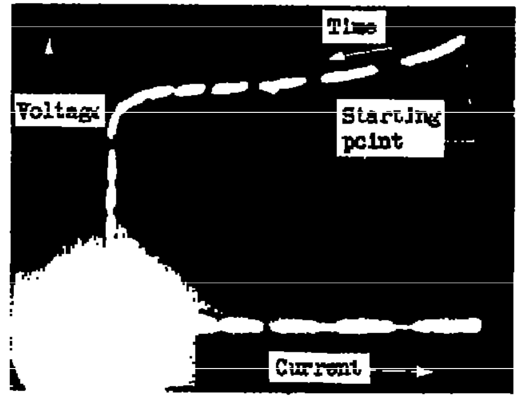
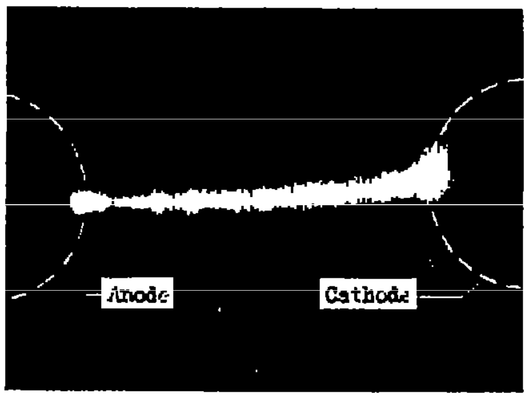


(a) Oscillogram of arc-glow discharge (reference 1).



(b) Oscillogram of glow discharge.



(c) Photograph of arc-glow discharge. Spacing, 0.65 inch.

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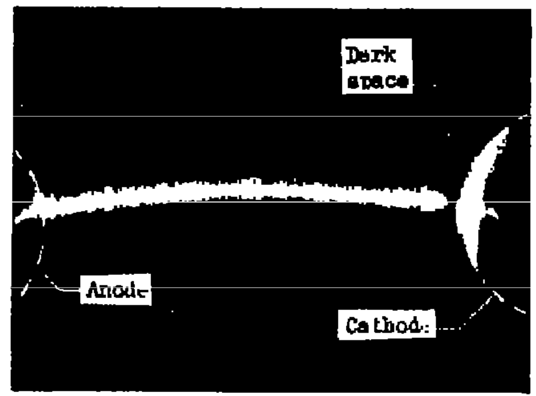

Photograph of glow discharge. Spacing, 0.65 inch.

Figure 4. - Oscillograms and photographs of spark discharges.

2394

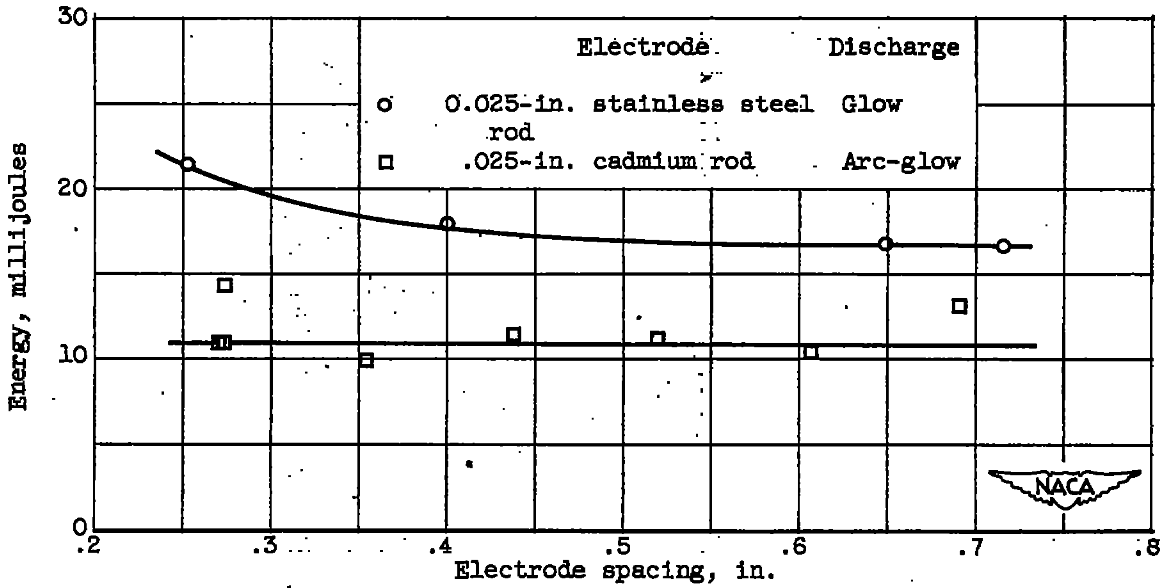

Figure 5. - Effect of electrode material and spacing on ignition energy of flowing propane-air mixture. Pressure, 3 inches mercury absolute; temperature, 80° F; fuel-air ratio, 0.0835.

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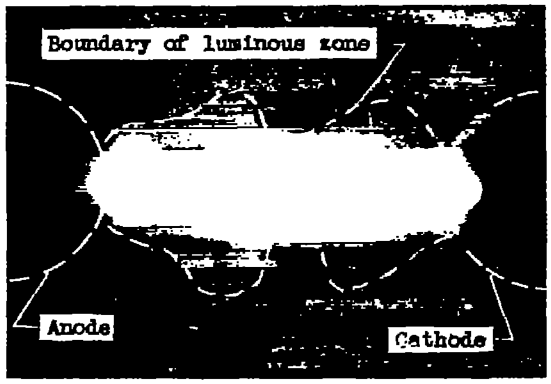
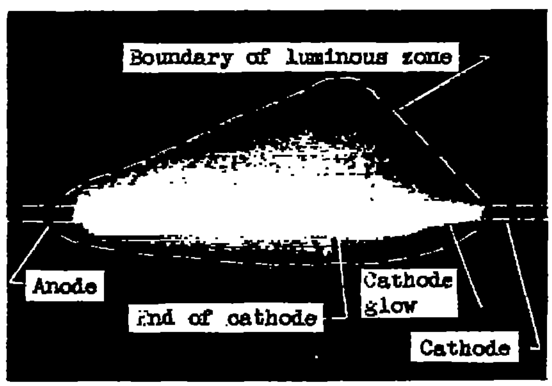


(a) Short-duration spark; sphere electrodes spaced 0.65 inch.



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(b) Long-duration spark; 0.025-inch rod electrodes spaced 0.65 inch.

Figure 6. - Long- and short-duration sparks at spark energies below those required for ignition.

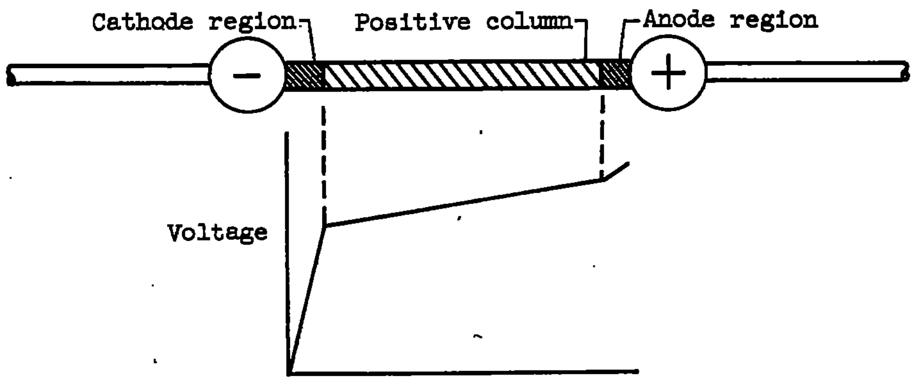

Figure 7. - Variation of voltage along constant-current discharge.

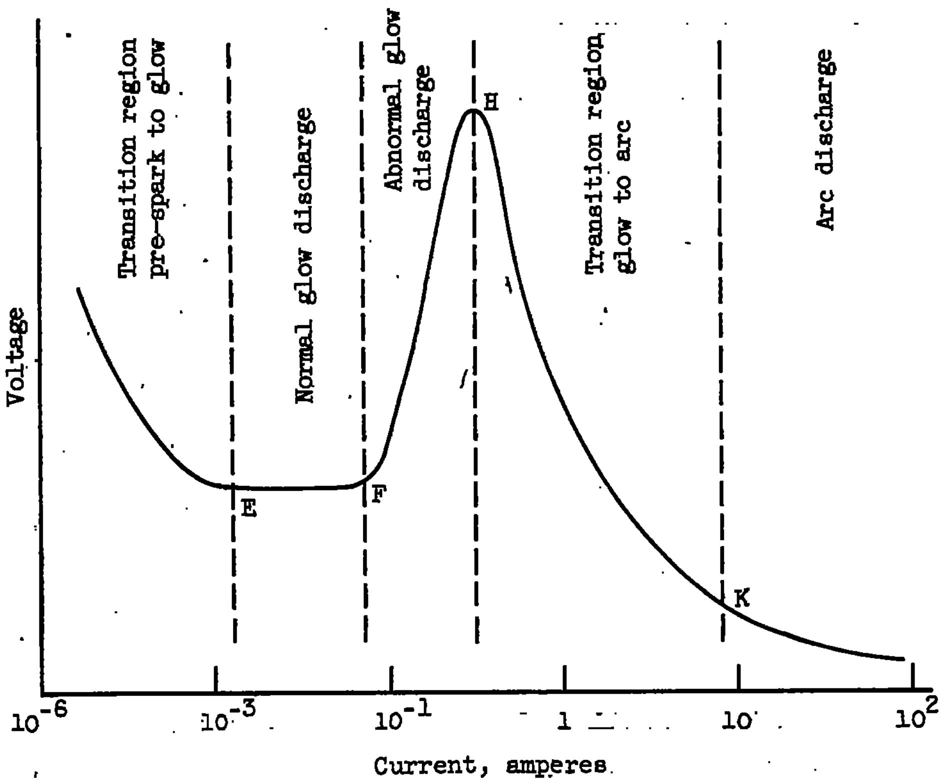

Figure 8. - Effect of discharge current on cathode voltage drop. (Redrawn from reference 9, p. 89.)

2394

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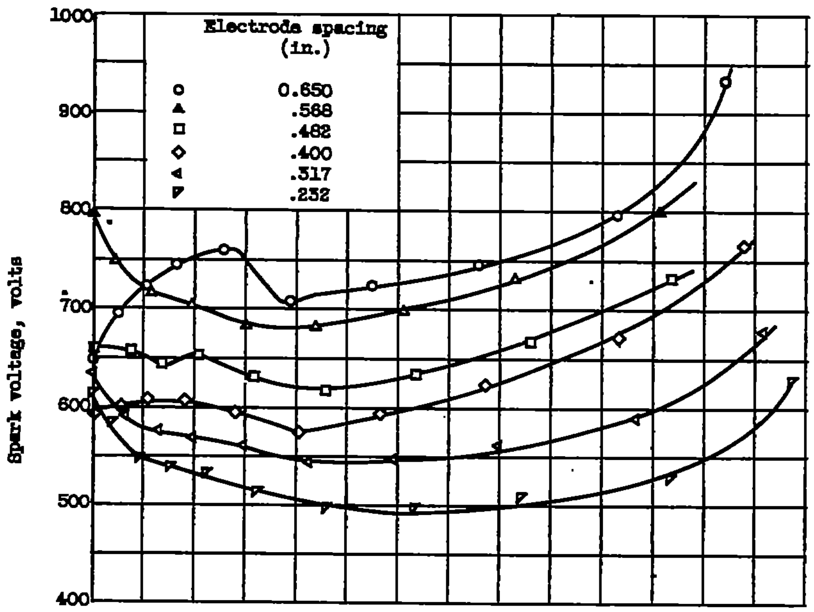
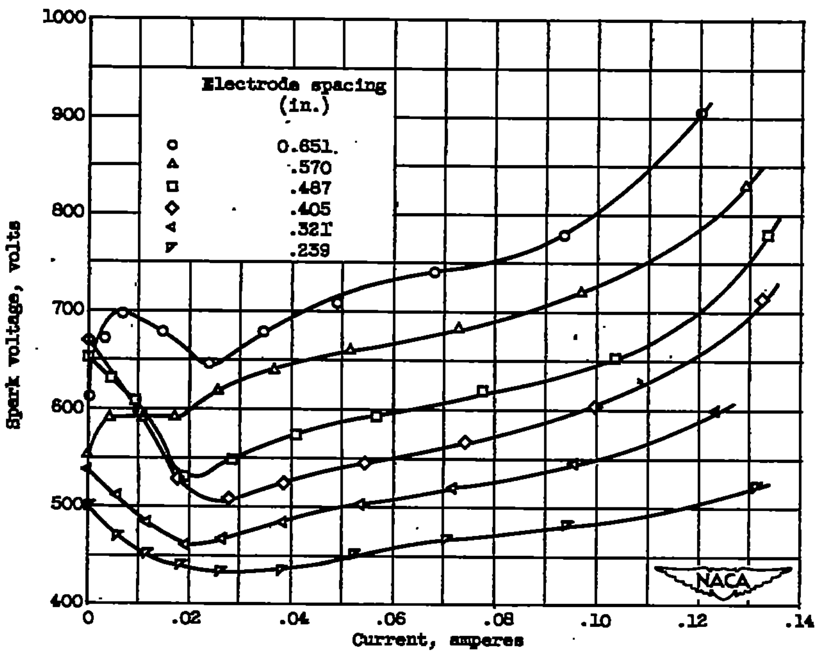
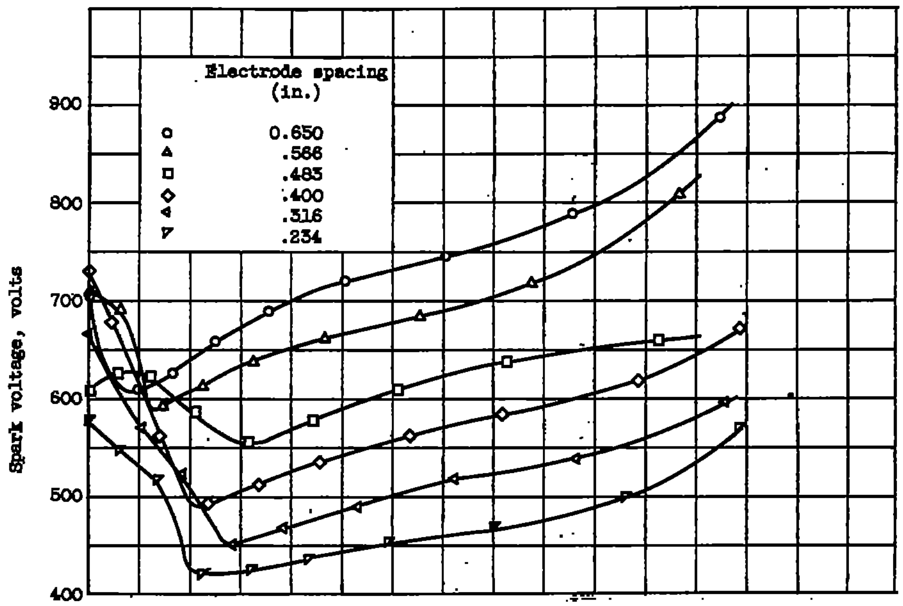


(a) Lead spheres.

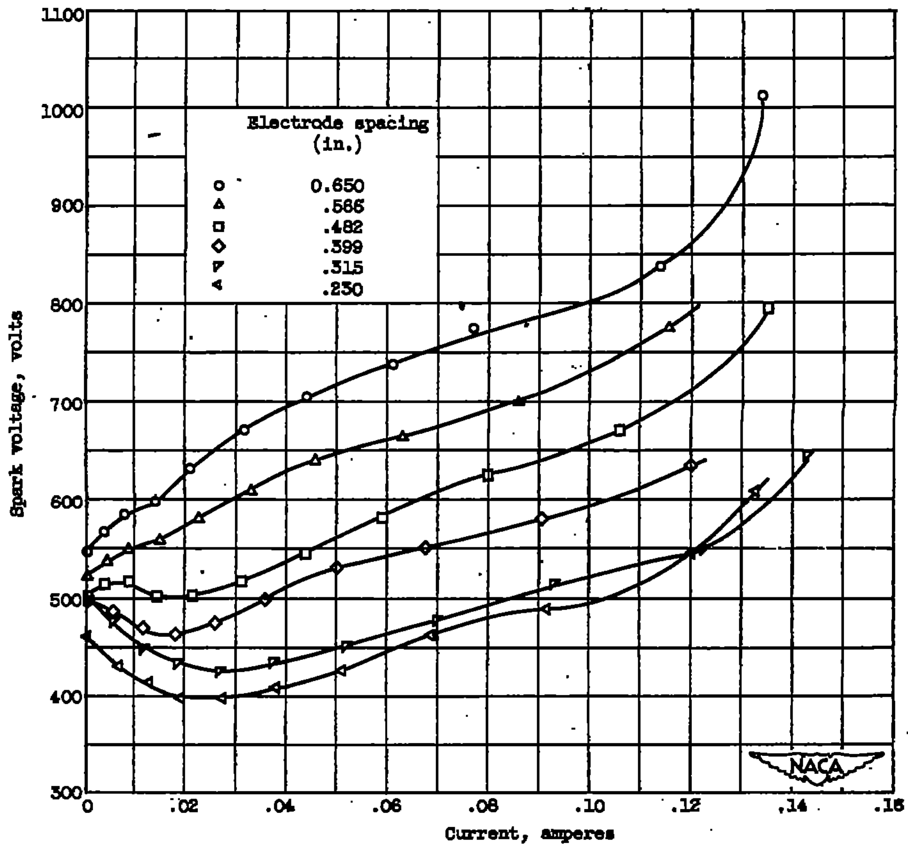


(b) Brass spheres.

Figure 9. - Effect of spark current and electrode spacing on spark voltage with electrodes of different materials.



(c) Cadmium spheres.



(d) Aluminum spheres.

Figure 9. - Continued. Effect of spark current and electrode spacing on spark voltage with electrodes of different materials.

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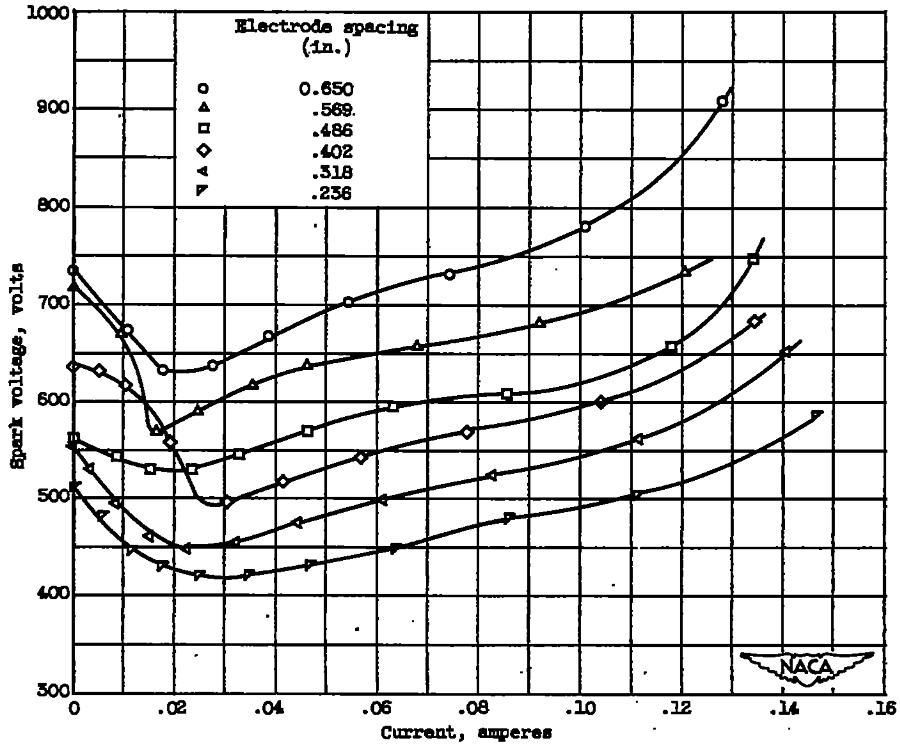

(e) Tungsten spheres.

Figure 9. - Concluded. Effect of spark current and electrode spacing on spark voltage with electrodes of different materials.

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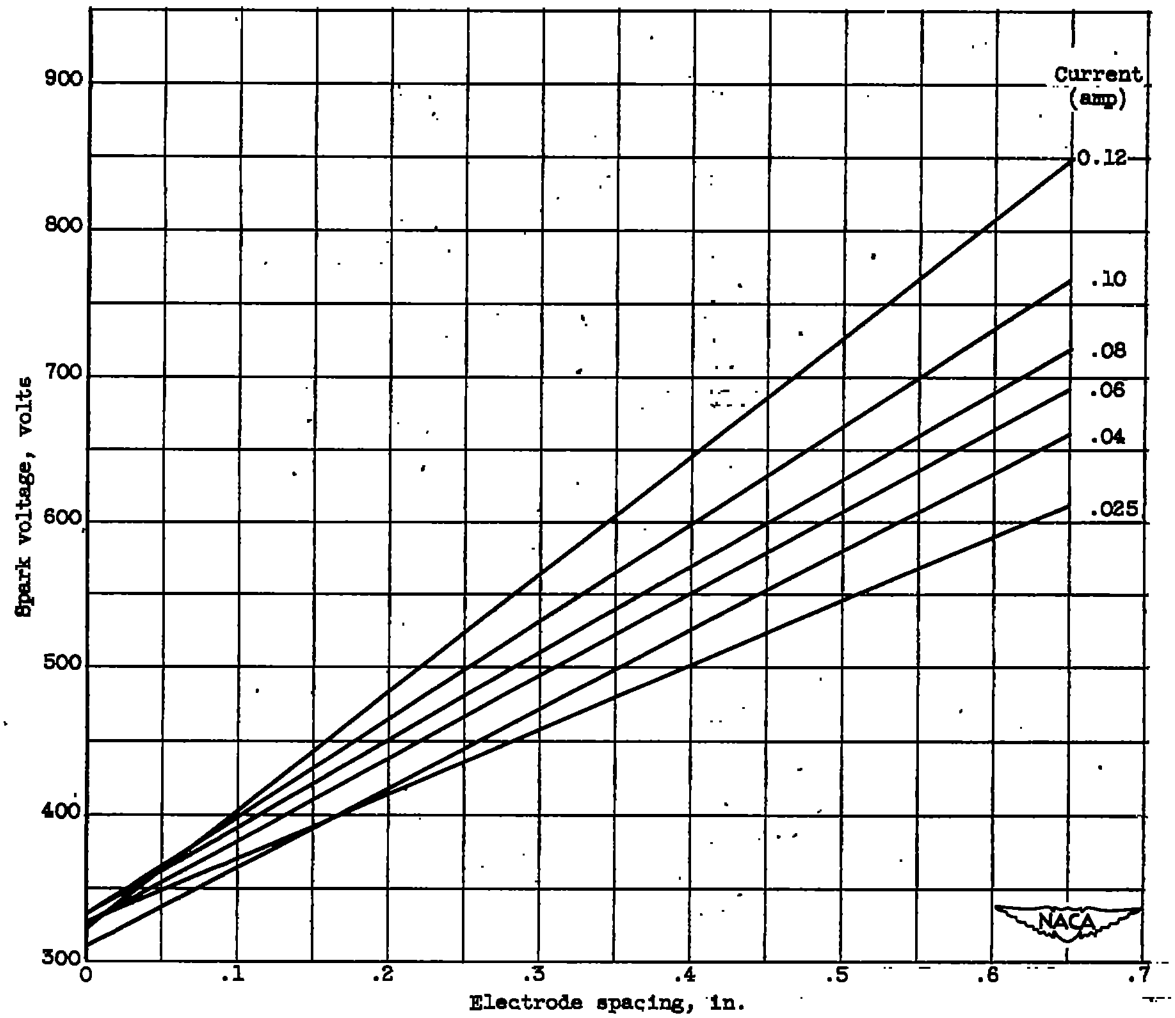

Figure 10. - Effect of electrode spacing on spark voltage for constant values of spark currents with brass electrodes.

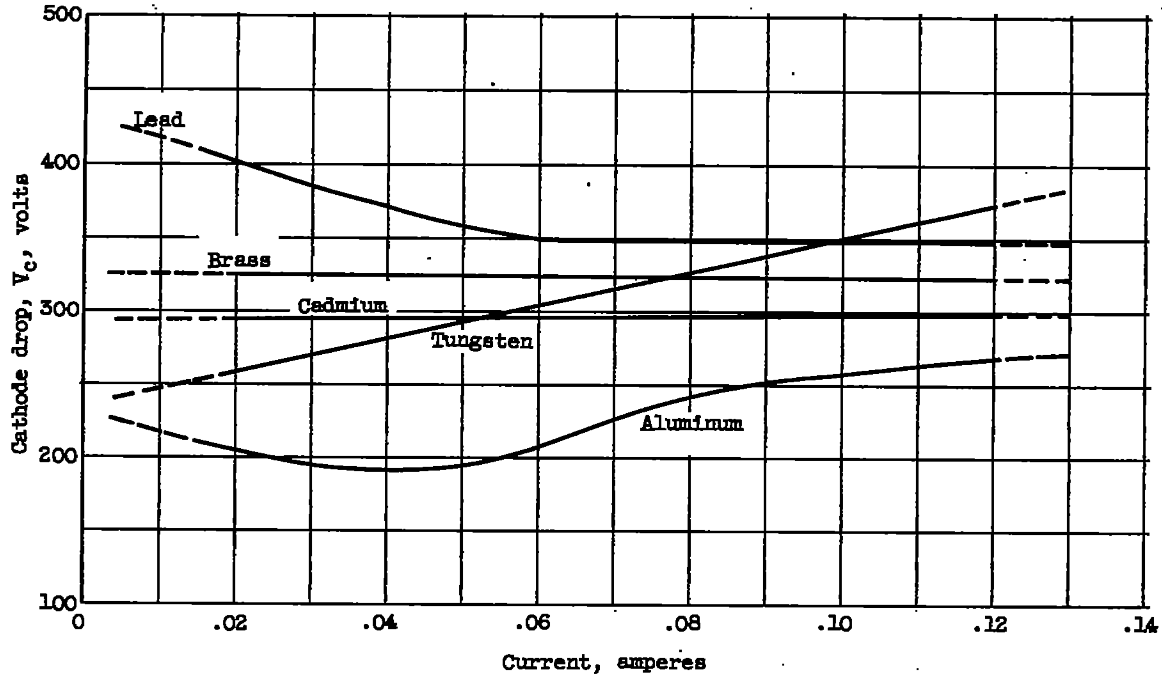

Figure 11. - Effect of current on cathode voltage drop for five electrode materials.

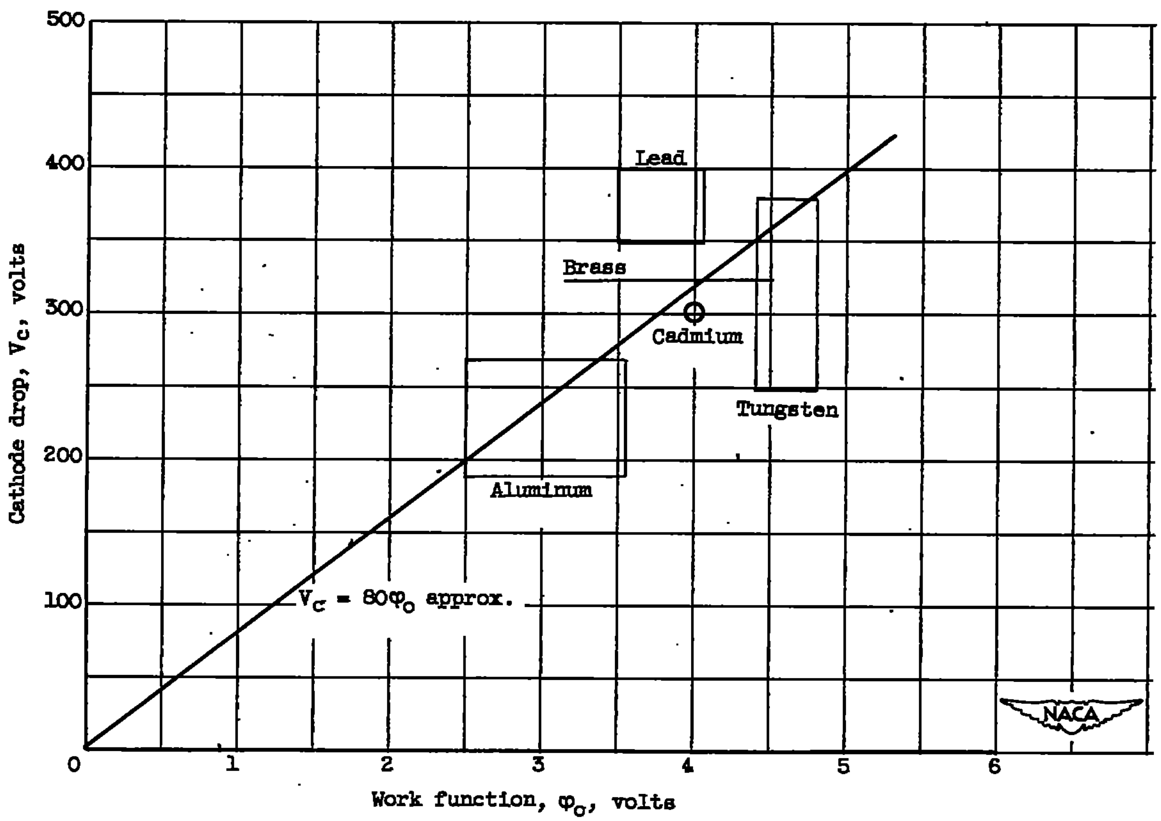

Figure 12. - Effect of work function on cathode voltage drop.

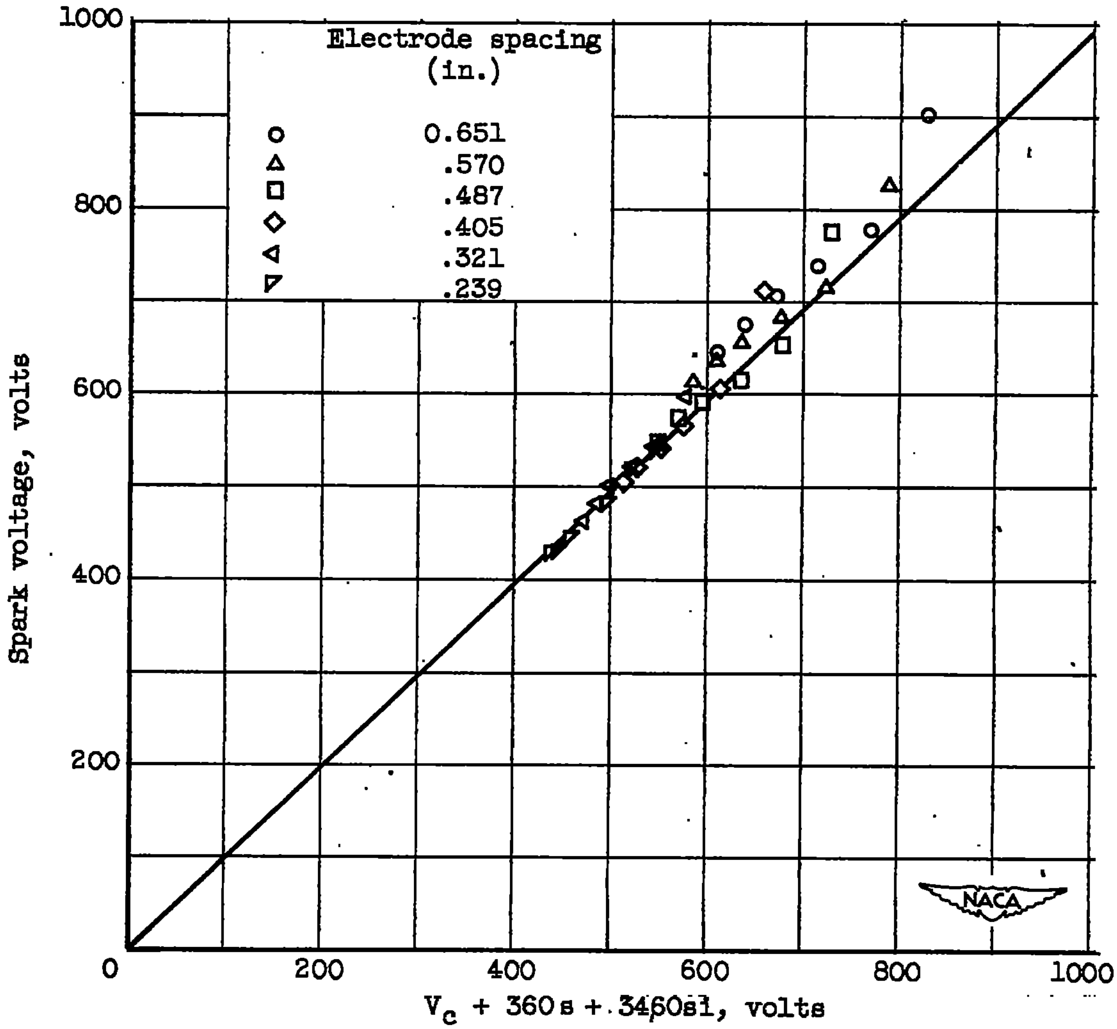

Figure 13. - Empirical correlation of spark voltage with cathode drop, electrode spacing, and spark current. Electrode spacing s, inches; current i, amperes; and cathode drop V_c, volts (325 for brass).